REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 28 July 2001	3. REPORT TYPE AND DATES COVERED Final 01 May 97-30 Apr 01

4. TITLE AND SUBTITLE
The Compressive Failure of Cracked Ice on Scales Large and Small

5. FUNDING NUMBERS
DAAG55-97-1-0138

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
35024.10-EV

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT	12 b. DISTRIBUTION CODE
Approved for public release; distribution unlimited.	

13. ABSTRACT (Maximum 200 words)

Experiments have established that size per se is not a factor in the compressive strength of ice, at least over the range from 10 mm to 1 meter. Irregular interfaces between ice and loading boundaries weaken ice and lead to non-simultaneous failure when the material is deformed within the regime of brittle behavior. Ice exhibits both Coulombic (under lower confinement) and plastic (under higher confinement) compressive shear faults. The study of ice has led to new physical insight into the compressive behavior of brittle, polycrystalline materials.

14. SUBJECT TERMS	15. NUMBER OF PAGES 5
	16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	**UNCLASSIFIED**	**UNCLASSIFIED**	**UL**

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

20010831 029

REPORT DOCUMENTATION PAGE (SF298)
(Continuation Sheet)

FINAL PROGRESS REPORT

ARO Contract NO.: DAAG55-97-1-0138
Title: The Compressive Failure of Cracked Ice on Scales Large and Small
P.I. Erland M. Schulson

STATEMENT OF THE PROBLEM STUDIED

The Issues: This research addressed the primary question of whether *size* affects the compressive strength of ice, an issue directly related to forces exerted by floating ice covers against docks, piers and other engineered structures. The work also addressed secondary questions that arose during the course of the study, issues related to the role of *boundary* conditions on brittle compressive strength, the effect of *cyclic loading* on compressive strength, the nature of *Coulombic vs plastic shear faults* in ice, and the *nature of compressive behavior* of ploycrystalline materials in general.

SUMMARY OF THE MOST IMPORTANT RESULTS

Chief Findings:

No Size Effect, but an Effect of Boundary Conditions: The experiments (91 in total) have shown that the unconfined compressive strength of S2 saline ice, loaded across the columns at -3 °C at strain rates spanning the ductile to brittle transition (10^{-6} s^{-1} to 10^{-2} s^{-1}), is essentially independent of size, over the range 0.15 m to 1 m. When added to earlier results, which showed that compressive strength of granular ice cubes of edge length 10 mm to 150 mm is also independent of size over that range, it would appear that size per se is not a factor in the unconfined compressive strength of ice. This is not to say, however, that larger pieces in the field will generally posses the same strength as smaller pieces in the laboratory. There, internal cracks and other large stress concentrators may conspire to weaken the material, particularly when rapidly loaded (i.e., on the brittle side of the transition). Also, irregular boundaries were found to trigger non-simultaneous failure at high deformation rates within the regime of brittle behavior, as has been shown to happen even with small ice cubes (Kuehn et al., 1993). Yet, when variations in the microstructure, in macrostructure and in boundary conditions are not at issue- more hypothetical, perhaps than practical- the study offers little to suggest that the physics of compressive failure depends on size.

The only differences that were detected between the smaller and larger specimens involved the strain rate sensitivity and the observed deformation damage at 10^{-4} s^{-1}. On the first point, the constant m (strain rate sensitivity factor) was lower for the larger samples than for the smaller specimens or published values, m=0.18 versus m=0.3, respectively. However, these experiments were not designed to evaluate the strain rate sensitivity of large versus small samples, so this apparent difference in m values is suggested as a topic for future research. On the fracture features, the differences are the intersecting bands of damage along the diagonals of the larger

specimens when deformed at 10^{-4} s^{-1}. This was not evident in the smaller specimens, which suggests that at least one damage mode has a characteristic length greater than edge length of the small cubes. This, too, requires further work. A manuscript on this work is in preparation.

Strengthening upon Cyclic Loading: Compression experiments on S2 fresh-water ice at -10° C deformed at $3x10^{-3}s^{-1}$ have revealed that the terminal compressive failure stress under across-column biaxial loading (σ_2/σ_1=0.075) increases by a factor of 1.5 upon cyclically loading (on-off) to progressively higher applied stresses. The effect saturates after about ten cycles. Cycling has no effect on the mode of failure which in every case occurred via Coulombic shear faulting (see below). However, cycling reduces the rate of damage accumulation, leading to the need to apply greater applied stresses to reach the point of micro-mechanical instability that marks the onset of terminal failure. The effect is interpreted in terms of stress relaxation at grain boundaries. A manuscript on this subject has been submitted to *Philosophical Magazine*.

Coulombic vs Plastic Compressive Shear Faults: We have explained a feature that has been reported in the literature several times following the sudden, terminal failure of polycrystalline ice Ih rapidly deformed under multiaxial compression.The feature is a narrow shear fault which is inclined by 45±5° to the direction of the most compressive stress. It is attended by either little or no cracking, distributed or localized, and by either little or no increase in volume. The terminal strength accompanying the fault, given as the difference between the greatest and the least principal stress, is independent of confining pressure and increases with increasing strain rate. The 45° fault has been interpreted in terms of localized plastic flow on planes of maximum shear stress. We term it a *plastic fault*. This kind of fault contrasts with another kind which is inclined by <45°, typically by ~ 30°, to the direction of the most compressive stress. This kind is attended by both distributed and localized microcracking, is two to three grain diameters wide in virgin material, and is accompanied by pressure hardening and by strain-rate softening. The <45° fault has been explained in terms of frictional crack sliding, crack growth and crack interaction, and has been modelled by incorporating a new, comb-crack triggering mechanism. The plane of the fault corresponds to a Coulombic conjugate plane whose orientation depends upon the coefficient of internal friction. We term it a *Coulombic fault*.The transition from Coulombic to plastic faulting can be accounted for quantitatively in terms of the suppression of frictional sliding, and localized plasticity can be explained in terms of adiabatic softening. A paper on this subject has been submitted to *Philosophical Magazine.*

Universal Compressive Behavior of Brittle Materials (In collaboration with Prof. C.E. Renshaw of Dept. of Earth Sciences, Dartmouth College): Brittle failure limits the compressive strength of ice and rock when rapidly loaded under low to moderate confinement. Higher confinement or slower loading results in ductile failure once the brittle-ductile transition is crossed. Brittle failure begins when primary cracks initiate and slide, creating wing cracks at their tips. Under little to no confinement, wing cracks extend and link together, splitting the material into slender columns which then fail. Under low to moderate confinement, wing crack growth is restricted and terminal failure is controlled by the localization of damage along a narrow band. Earlier investigators proposed that localization results from either the linkage of wing cracks or the buckling of micro-columns created between adjacent wing cracks. Our new observations of compressive failure in ice suggest a new mechanism whereby localization initiates due to the bending-induced failure of slender micro-columns created between sets of secondary cracks emanating from one side of a primary crack. Analysis of this mechanism leads to a closed-form, quantitative model that only depends on independently measurable

mechanical parameters. Model predictions for both the brittle compressive strength and the brittle-ductile transition are consistent with data from a variety of crystalline materials, offering for the first time quantitative evidence for universal processes in brittle failure. A paper on this subject has been accepted by *Nature* (in press).

LISTING OF PUBLICATIONS AND TECHNICAL REPORTS SUPPORTED BY THIS GRANT:

a) Published in Peer-reviewed journals

"Non-linear rate dependent deformation under compression due to state variable friction", C.E. Renshaw and E.M. Schulson, *Geophys. Res. Letters*, **25**, 1198, 1998.

"On the initiation of shear faults during brittle compressive failure: A new mechanism", E.M. Schulson, D. Iliescu and C.E. Renshaw, *J. Geophysical Research*, **104**(B1), 1999.

"The brittle compressive failure of orthotropic ice under triaxial loading", E.M. Schulson and E. T. Gratz, *Acta mater.*, **47**(3), 1999.

"The structure and mechanical behavior of ice", E.M. Schulson, *Journal of Materials*, **51**, Feb. 1999.

"Universalbehavior in compressive failure of brittle materials", C.E. Renshaw and E.M. Schulson, *Nature* (2001, in press).

"Brittle failure of ice", E.M. Schulson, *Eng. Fract. Mech.* (2001, in press).

"Fracture of Ice", E.M. Schulson, *Eng. Fract. Mech.* (2001, in press)

"Fracture of Ice on Scales Large and Small", E.M.Schulson, in "*Scaling Laws in Sea Ice Mechanics*" ed. J. Dempsey, Inter. Union of Theor. & Appl. Mech. (IUTAM), Klluwar Acad. Publishers, Dordrecht, 2001 (in press)

b) Published in Non-Peer-review journals or in conference proceedings

"Macroscopic compressive shear faults in S2 columnar ice", D. Iliescu and E.M. Schulson, *Proc. 14th Interational Symposium on Ice,* 553-558, 1998.

"On the triggering of shear faults during brittle compressive failure: A new mechanism", E.M. Schulson, D. Iliescu and C.E. Renshaw, *Mater. Res. Soc. Symp. Proc.*, **539**, 1999.

c) Presented at meetings, but not published in conference proceedings

None

d) Submitted, but not yet published

"Contributions to Brittle Compressive Failure of Ice", Daniel Iliescu, Ph.D. thesis, Thayer School of Engineering, Dartmouth College, November 2000.

"On Compressive Shear Faults in Ice", E.M. Schulson (submitted, Phil. Mag.A 2001)

e) Technical reports submitted to ARO

None

LIST OF PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT.

Daniel Iliescu, Ph. D.
Jeffrey Melton, Ph.D.

REPORT OF INVENTIONS

None

MEMORANDUM OF TRANSMITTAL

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CONTRACT/GRANT NUMBER: DAAG55-97-1-0138

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is forwarded for your information.

Sincerely,

Erland M. Schulson
Professor of Engineering

Enclosure 3